Impacts of Model Resolutions and Initial Conditions on Predictions of the Asian Summer Monsoon by the NCEP Climate Forecast System

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ABSTRACT

A series of 60-day hindcasts by the Climate Forecast System (CFS) of the National Centers for Environmental Prediction is analyzed to understand the impacts of atmospheric model resolutions and initial conditions on predictions of the Asian summer monsoon. The experiments, for the time period 2002–06 and with 14 ensemble members, are conducted at resolutions of T62, T126, and T254. They are initialized every 5 days from May to August, using the operational global atmospheric data assimilation system and operational global ocean data assimilation. It is found that, in predicting the magnitude and the timing of monsoon rainfall over lands, high model resolutions overall perform better than lower model resolutions. The increase in prediction skills with model resolution is more apparent over South Asia than over Southeast Asia. The largest improvement is seen over the Tibetan Plateau, at least for precipitation. However, the increase in model resolution does not enhance the skill of the predictions over oceans. Overall, model resolution has larger impacts than do the initial conditions on predicting the development of the Asian summer monsoon in the early season. However, higher model resolutions such as T382 may be needed for the CFS to simulate and predict many features of the monsoon more realistically.

1. Introduction

Prediction of the Asian summer monsoon, which affects about half of the population of the world and is linked to many natural disasters such as droughts and floods, has long been a challenging component in operational weather and climate predictions, both statistical and dynamical, in many countries. The challenge comes from the complex variations of the monsoon, which interacts strongly with oceanic and land surface processes and large-scale atmospheric patterns of natural variability (e.g., Shukla 1987; Meehl 1994; Zhang et al. 1996; Kripalani and Kulkarni 1997; Webster et al. 1998; Chang et al. 2001; Yang et al. 2004; Yoo et al. 2006; Zhang and Zuo 2011), as well as the dynamical and thermal conditions of the Tibetan Plateau (Li and Yanai 1996; Kitoh 2004; Nan et al. 2009; Zuo et al. 2011). It also comes from the capability of numerical models, since they still face many difficulties in predicting monsoon variations accurately at present. Nevertheless, state-of-the-art models often yield encouraging outcomes and provide important potential for improving monsoon predictions and have been widely used to understand and predict various features of the monsoon (e.g., Yang and Lau 1998; Kang et al. 2002; Wu and Kirtman 2004; Yoo et al. 2004; Kusunoki et al. 2006; Kripalani et al. 2007).

Enhancements in model resolution and initial conditions (ICs), among others, have been considered important factors for improving the skill of monsoon predictions (Reynolds et al. 1994; Sperber et al. 1994;
Unsurprisingly, improvements have been particularly apparent over regions with complex features of topography and land–ocean distributions (e.g., Yang et al. 2008b; Xu et al. 2010). Nevertheless, the improvements in monsoon simulations and predictions with enhancements in model resolutions and ICs are also different from one model to another, and experiments with decent or capable numerical models are among the critical factors for attaining these improvements.

The Climate Forecast System (CFS) of the National Centers for Environmental Prediction (NCEP) is an operational global coupled climate prediction system. The first version of the system, which consists of the NCEP Global Forecast System (GFS), the Geophysical Fluid Dynamics Laboratory’s Modular Ocean Model (GFDL MOM V3), and the Oregon State University (OSU) land surface model, had become operational since August 2004 (for details, see Saha et al. 2006). The performance of the CFS on simulating and predicting the Asian monsoon has been assessed comprehensively and various encouraging features about different aspects of the monsoon have been discussed. Yang et al. (2008b) provided a comprehensive assessment of the CFS in simulating and predicting the Asian summer monsoon. The model predicts the large-scale features of the monsoon such as the Webster–Yang monsoon index (Webster and Yang 1992) with significant skill by several months in advance, although the skill can be largely attributed to the impact of El Niño–Southern Oscillation (also see Drbohlav and Krishnamurthy 2010; Lee et al. 2011). Yang et al. (2008b) also revealed an apparent weak bias of the Asian monsoon in the CFS and attributed it to a cold bias over the Asian continent related to the simplicity of the land surface model in the forecast system. Indeed, improvements in the land surface model significantly reduced the cold bias in the CFS (Yang et al. 2011). On interannual time scales, Liang et al. (2009) and Gao et al. (2011) revealed that the most predictable patterns of the Asian summer monsoon rainfall and the East Asian midsummer mei-yu rainbands were the most dominant modes of the observed monsoon rainfall and mei-yu rainbands. Several studies (e.g., Yang et al. 2008a; Rai and Krishnamurthy 2011; Achuthavarier and Krishnamurthy 2011; Yang et al. 2011) also examined the skill and errors of monsoon simulations and predictions on intraseasonal and shorter time scales. In particular, Rai and Krishnamurthy (2011) evaluated the skill of predicting the Indian summer monsoon rainfall using daily information from GFS hindcasts. The authors found that error growth was slower for predictions initiated in May (compared to the predictions initiated in July) and for predictions initiated

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during the normal phase of the intraseasonal variability (compared to those initiated during the active or beak phases). Janakiraman et al. (2011) suggested that some errors of monsoon prediction could be reduced with improvements in ocean modeling over the equatorial Indian Ocean. In addition, Li and Yang (2010) showed that the CFS was skillful in simulating and predicting the East Asian winter monsoon. Since 2011, the second version of the system, with enhanced models for the atmosphere (GFS, in horizontal resolution T126), oceans (GFDL MOM V4), and land (the NCEP, OSU, U.S. Air Force, and Hydrologic Research Laboratory land models), has become operational (S. Saha et al. 2012, unpublished manuscript). Assessment of the skill of simulations and predictions of the Asian monsoon by the new version of the CFS is just getting under way.

In spite of the several studies related to the simulation and prediction of the Asian monsoon by the CFS reviewed above, the impacts of model horizontal resolution and ICs on the skill of predictions of the Asian summer monsoon have not been investigated by any purposely conducted experiment with the particular system. Yang et al. (2008b) have briefly shown the improvement in simulating the Asian summer monsoon from resolution T62 to resolution T126 over the Tibetan Plateau and the tropical Indian Ocean, but the
Achuthavarier and Krishnamurthy (2010) claimed that the improvement in monsoon simulation with model resolution was only marginal. Many of the studies reviewed above have also analyzed the features of monsoons predicted at different lead months. In this study, we deliberately conduct several experiments with the CFS to understand the impacts of model resolutions and ICs on the skill levels of the predictions of the Asian summer monsoon over different domains. We carry out these experiments using three model resolutions and various ICs in two different data assimilation systems (see description in section 2).

In the subsequent section, we provide a brief description of the model experiments and the observational datasets used for validation of the model output. The impacts of the model resolutions and ICs on the skill of the monsoon predictions are discussed in sections 3 and 4, respectively. In section 5, we compare the model results using the ICs employed by two different data assimilation systems. A summary of the results obtained in this study is given in section 6.

2. Model experiments and observational datasets

The model output analyzed in this study is from several experiments run with the NCEP CFS. In these experiments, the simulations of the atmospheric model, the NCEP GFS (Moorthi et al. 2001), have horizontal resolutions of T62 (about 200 km × 200 km), T126 (about 100 km × 100 km), and T254 (about 50 km × 50 km). The experiments for each resolution use ICs from the NCEP Global Data Assimilation System (GDAS) and the Climate Data Assimilation System (CDAS). The GDAS uses the up-to-date version of the GFS and its assimilation techniques and provides the best estimate of the atmospheric state at a given time. However, as models are systematically being improved with time, the “history” of the atmosphere as provided by GDAS has a dependency on the model numerics. The CDAS, known as the NCEP/Department of Energy Global Reanalysis 2, assimilates observed data from 1979 to the present using an older version of the GFS and its assimilation techniques. The use of “frozen” versions of the atmospheric model and its assimilation techniques provides a consistent history of the atmosphere that does not depend on model numerical formulations. In all experiments, the GFS has 64 sigma layers in the vertical, with the top layer at 0.2 hPa. The oceanic component, the GFDL MOM V3.0 (Pacanowski and Griffies 1998), and the land component, the two-layered OSU land surface model (Mahrt and Pan 1984), of the CFS are unchanged in all the experiments. To facilitate discussions, we refer to these experiments as GDAS_T62, GDAS_T126, GDAS_T254, CDAS_T62, CDAS_T126, and CDAS_T254, named, respectively, according to the types of ICs and resolutions. All experiments are integrated.
for 60 days for each year during 2002–06, initialized every 5 days from 23 May to 11 August. Only the results from the first four ICs (23 and 28 May and 3 and 8 June) are analyzed.

The observation datasets used in this study are the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), the NCEP–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996), and the high-resolution blended real-time global sea surface temperature (SST) analysis (RTG_SST; Thiebaux et al. 2003). All data adopt the same resolution of 2.5° × 2.5° latitude and longitude. The “climatological” values of this work refer to the values averaged from 2002 to 2006.

3. Impact of model resolutions

In this section, we focus on the impact of model resolution on predictions of the Asian summer monsoon. We first analyze the ensemble means of experiments GDAS_T62, GDAS_T126, and GDAS_T254 using the ICs of 23 and 28 May and 3 and 8 June. A comparison between results from experiments using the GDAC ICs and the CDAS ICs will be given in section 5.

Figure 1 shows the patterns of 5-yr mean precipitation and 850-hPa winds from 10 June to 19 July for observations and CFS experiments at different resolutions. During early summer (from 10 June to 19 July), the monsoon becomes established over most of tropical Asia,
featuring vigorous tropical westerly flow. Southerly winds appear over East Asia, resulting from the tropical westerly flow over the Indian Ocean, the cross-equatorial southerly flow over the Maritime Continent, and the southeasterly flow to the west of the subtropical western Pacific high. Precipitation totals of over 6 mm day$^{-1}$, which is commonly used as a criterion to mark the beginning of the rainy season in the monsoon region (e.g., Lau and Yang 1997), can be observed over tropical Asia and subtropical East Asia, especially the heavy rainfall over the west coasts of the Indian Peninsula (IP), the Indochina Peninsula (ICP), the Bay of Bengal (BOB), the South China Sea (SCS), and the western Pacific warm pool.

The model experiments at all resolutions capture the major features of the monsoon circulation at the lower troposphere, which include the westerly wind from the Arabian Sea to the SCS, the southerly wind over eastern China, and the cross-equatorial flow from the Southern Hemisphere over Somali and the Maritime Continent (see Figs. 1b–d). However, the CFS produces an overall weaker-than-observed summer monsoon circulation pattern (Figs. 2a–c; also see Yang et al. 2008b). An anticyclone centered over the BOB and a cyclone over the western Pacific are found in the differential winds between the CFS and the observations. Due to the weak monsoon circulation, monsoonal precipitation is underestimated over the IP, East Asia, the SCS, and the western Pacific. Moreover, the distribution of CFS rainfall seems to be influenced strongly by topographic features. Indeed, centers of heavy rainfall are all located upstream of high topography, including the west coasts of the IP and ICP and most of the Maritime Continent.

The differences in precipitation among various CFS experiments at different resolutions are also shown in Fig. 2. Overall, the increase in model resolution improves the simulation of monsoon rainfall over land. From T62 to T254, the problems of dry bias over India and wet bias over the Tibetan Plateau lessen appreciably (Figs. 2a–c). The increase in model resolution also strengthens the underestimated monsoon circulation. However, the experiments at higher resolution seem to worsen the dry bias over the SCS and the western Pacific and the wet bias over the Maritime Continent. This problem may be due to the anomalous northeasterly flow from the western Pacific to the Maritime Continent,
as shown in Figs. 2d–f, which leads to anomalous convergence over the Maritime Continent and divergence over the western Pacific. Figures 2d–f also show that, for rainfall simulations, improvement in the dry bias over India largely takes place from T126 to T254. However, deterioration of the dry bias over the Philippine Sea and nearby waters occurs more apparently from T62 to T126. Errors in simulating the lower-tropospheric circulation (over Southeast Asia) that seem to be associated with the rainfall deterioration also mainly occur from T62 to T126. In addition, a reduction in the wet bias over the Tibetan Plateau can be seen both from T62 to T126 and from T126 to T254.

Since major monsoon centers are often located over oceans (see Fig. 1a), the CMAP precipitation dataset possesses an advantage in depicting the features of large-scale rainfall patterns. Nevertheless, the CMAP dataset also has a shortcoming in its low resolution and some may question its representation of monsoon features compared with other datasets of higher resolutions. Here, we compare the CMAP data with a high-resolution (0.5° × 0.5° latitude and longitude) gauge-based analysis of daily precipitation (Xie et al. 2007) over land since the latter only covers land portions. Similar rainfall patterns can be found between the two panels in Fig. 3. In both datasets, the heaviest rainfalls occur over western India, Bangladesh, the southwestern Indochina Peninsula, the northern Philippines, southern China, Korea, and southern Japan. (The lack of heavy rainfall over Myanmar may not be real.) The northern extents of heavy monsoon rainfall, such as those measured by the 6 mm day⁻¹ contour, are also similar between the two datasets. Figure 3 suggests an ability of the CMAP data to measure large-scale features of monsoon rainfall patterns, at least over land.

With the aid of the high-resolution data over land, we further compare the rainfall averaged over 25°–35°N, 75°–100°E between the gauge-based precipitation analysis and the CFS simulations. Figure 4 shows that the CFS at all three resolutions overestimates the rainfall over the Tibetan Plateau. However, improvements in simulating the regional rainfall are apparent from T62 to T126 and from T126 to T254. During the entire analysis period, T254 always clearly performs better than does T62.

Since all of the experiments use the same ocean model, the difference in SST indicates a possible influence of the atmosphere on the oceans. The CFS performs well in SST predictions, especially for tropical oceans (Fig. 5). It captures the warm pools from the western Pacific to the eastern Indian Ocean and from the western Atlantic Ocean to the eastern Pacific realistically. It also captures the cold tongues in the eastern Pacific and the eastern Atlantic. The difference between the CFS and

![Fig. 7. As in Fig. 1, but for the WVF integrated from the surface to 300 hPa (kg m⁻¹ s⁻¹).](image)
observed SST over most of the tropical oceans (30°S–30°N) is below 1°C (Figs. 6a–c). In the Pacific, there are cold biases in the northern Pacific and the eastern tropical Pacific and a warm bias in the western Pacific warm pool. With the increase in model resolution, the cold biases described above are reduced significantly (Figs. 6d–f) and the improvement mainly occurs from resolution T126 to resolution T254 (Fig. 6e). However, the western Pacific warm pool becomes even warmer, especially from T62 to T126 (Fig. 6d), due to the increased low-level northeasterly wind and the decreased precipitation in situ.

Water vapor transportation is a key process in the monsoon rainfall cycle, and abundant vapor import often leads to excessive rainfall during the monsoon season (e.g., Lau and Yang 1996; Sun et al. 2011). Figures 7 and 8 present the climatological patterns of water vapor flux (WVF) for the observations and the CFS, as well as their differences. In the observations, the WVF pattern indicates a notable channel of water vapor transportation from the Indian Ocean to far eastern Asia. Coincident with the weak monsoon circulation in the CFS discussed above, the transportation of water vapor over the southern Indian Ocean and the entire monsoon region is weaker than observed, with similar patterns in different experiments (e.g., Figs. 8a–c). As in the anomalous low-level circulation, the differential WVF between the CFS and the observations exhibits an anticyclonic pattern over the IP and a cyclonic pattern over the western Pacific. The reverse differential WVF pattern seen in the observations reduces the water vapor that arrives at the monsoon region, leading to the dry bias shown in Fig. 2. The experiments with higher resolution favor an increase in precipitation in the monsoon region. However, the excessively strong westward WVF from the
western Pacific to the eastern Indian Ocean leads to a poorer prediction of the precipitation over the western Pacific (larger dry bias) and the Maritime Continent (larger wet bias). Figures 8d–f indicate that larger errors occur from T62 to T126, compared to those from T126 to T254, consistent with the features shown in Figs. 2d–f for differences in rainfall.

We further compute the budget of the water vapor transportation for four areas in the tropical Asian monsoon region, for both the observations and the CFS experiments. In Fig. 9, the arrows with numbers beside them indicate the total water vapor fluxes across the boundaries, and the number inside each box denotes the net value of the water vapor budget over the specific domain. Over the Asian monsoon region, the water vapor entering from the western boundary is the major water vapor source. Although part of the water vapor from the Indian Ocean remains in tropical Asia, most of it is transported to the subtropical region of East Asia. As shown by the net water vapor budget, the atmospheric columns over the Maritime Continent, IP, and SCS gain water vapor, with a maximum over the Maritime Continent. However, the atmospheric column over ICP loses water vapor.

The water vapor budget in GDAS_T62 is roughly similar to the observed, including both the net values and the fluxes crossing boundaries. As described above, although precipitation is underestimated over tropical Asian land surfaces, the upstream precipitation to the west of high topography is much larger than the observed. Therefore, the net WVF in the CFS over tropical Asia is larger than that observed. However, due to the overestimation of southerly water vapor flux to the SCS, the net budget over the Maritime Continent is smaller than observed. As seen from Figs. 9c,d, enhanced model resolution does not necessarily improve the simulations of the water vapor flux. Indeed, the meridional fluxes across the northern and southern boundaries of the Indian monsoon region and the zonal fluxes across the western boundary of the Maritime Continent are inconsistent with those in the observations. As a result, the net WVF over the SCS and over the Maritime Continent decreases noticeably in the experiments with higher resolution, associated with the decrease in precipitation shown in Fig. 2.

We also examine patterns of precipitation evolution in the CFS experiments along 70°–90°E, 90°–110°E, and 110°–130°E, which delineate the rainfall over three major longitude bands within the Asian monsoon region (Fig. 10). The rainband over the ICP, a place of the earliest onset of the Asian summer monsoon (usually in May), is located steadily at 10°–20°N without notable meridional shift from mid-June to mid-July. In the Indian monsoon region, a rainband moves northward from 10° to 25°N, with another quasi-stationary rainband to the south of the equator. There are also two rainbands over East Asia: one is the subtropical monsoon rainband and the other is the tropical monsoon rainband. Both rainbands exhibit notable northward movements.

The mean patterns in Figs. 1 and 2 have already shown that predictions of the precipitation over land improve with increasing model resolution. The cross-section plots of time and latitude in Fig. 10 also demonstrate this improvement by the CFS. More realistic evolution of the
Fig. 10. Latitude–time cross sections of climatological (2002–06) pentad precipitation along (left) 70°–90°E, (middle) 90°–110°E, and (right) 110°–130°E for (a) observations and (b) GDAS_T62, (c) GDAS_T126, and (d) GDAS_T254.
precipitation over the IP occurs in experiments with higher resolution. Especially apparent is the improvement that can be found over the southern slope of the Tibetan Plateau (in the IP longitude band) in GDAS_T254. However, the problem with terrain influence on precipitation over the ICP has not been fully corrected, so that heavy rainfall is always located at 20°–30°N. Over East Asia, the variability of the subtropical rainband is captured by the CFS at various resolutions, but the strength of the tropical rainband over the SCS becomes weaker with increasing model resolution, as pointed out before. The improvement in simulating the rainfall over the IP from T62 to T254 and the deterioration when simulating the rainfall over 110°–130°E can also be clearly seen in the differences in rainfall over these longitude bands between CFS and the observations (figure not shown).

Figure 11 shows the curves for precipitation averaged over three subdomains of the Asian summer monsoon: IP (10°–20°N, 70°–90°E), ICP (10°–20°N, 90°–110°E), and SCS (10°–20°N, 110°–130°E). Overall, the predicted precipitation over the IP is more similar to the observations than is the precipitation over the ICP and SCS. The root-mean-square errors (RMSEs) of GDAS_T62, GDAS_T126, and GDAS_T254 are 1.77, 1.63, and 1.22 mm day⁻¹, respectively (see Table 1). The largest error is found over the SCS, where the RMSE values increase with model resolution, in agreement with the results shown above.

In short, enhanced model resolution in the NCEP CFS improves the skill of the predictions of the Asian monsoon circulation and precipitation over land especially over terrain regions. However, the increase in model resolution cannot improve the skill of prediction of the precipitation over the SCS and the western Pacific. The warm bias over the western Pacific warm pool is probably a major problem of the CFS with higher resolution, for which the cause is still unknown.

### Table 1. RMSEs of precipitation averaged over the IP (10°–20°N, 70°–90°E), the ICP (10°–20°N, 90°–110°E), and the SCS (10°–20°N, 110°–130°E) in GDAS and CDAS experiments.

<table>
<thead>
<tr>
<th>Domain</th>
<th>GDAS</th>
<th>CDAS</th>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>T62</td>
<td>1.77</td>
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<td>T126</td>
<td>1.63</td>
<td>2.29</td>
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<tr>
<td>T254</td>
<td>1.22</td>
<td>1.94</td>
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<tr>
<td>ICP</td>
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<tr>
<td>T62</td>
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<tr>
<td>T126</td>
<td>3.04</td>
<td>2.51</td>
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<tr>
<td>T254</td>
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<td>SCS</td>
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<tr>
<td>T62</td>
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<tr>
<td>T126</td>
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<td>5.57</td>
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<tr>
<td>T254</td>
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4. Impact of initial conditions

We now compare the GDAS_T254 experiments initialized from four initial dates—23 May, 28 May, 3 June, and 8 June—to assess the influence of the initial conditions on CFS’s performance. For convenience, we refer to these experiments as IC23MAY, IC28MAY, IC03JUN, and IC08JUN, respectively.

The predictions for the period from 11 June to 19 July using different initial conditions have similar error patterns in precipitation and 850-hPa winds (Fig. 12), which are also similar to those of the ensemble means shown in Fig. 2. Although there is no apparent relationship between prediction skill and the ICs, the differences between two sequent ICs imply some interesting features. For example, the difference between IC28MAY and IC23MAY displays positive values for precipitation and a cyclonic circulation in 850-hPa winds over 10°–20°N, 60°–120°E (Fig. 12e). The difference between IC03JUN and IC28MAY is negative for precipitation and anticyclonic for 850-hPa winds (Fig. 12f). In the third sequent pair (IC08JUN–IC03JUN), the difference turns positive for precipitation and cyclonic for 850-hPa winds again (Fig. 12g). These features suggest an effect of intraseasonal oscillation contained in the ICs on CFS prediction. They also imply that the errors in CFS themselves exhibit
intraseasonal oscillations (Y. Fun 2011, personal communication).

Illustrated by the time–latitude cross sections of the differences in precipitation over the IP (70°–90°E), ICP (90°–110°E), and SCS (110°–130°E) between the observations and GDAS_T254 experiments, the errors in the CFS experiments integrated from different ICs exhibit a similar distribution pattern of similar magnitude (Fig. 13). Consistent with the ensemble means, precipitation predictions are best over the IP and worst over the SCS in all of the GDAS_T254 experiments (Fig. 14). In addition, the differences among the experiments with various ICs are smaller than the differences between the CFS predictions and observations.
FIG. 13. (a) Latitude–time cross sections of differences in climatological (2002–06) pentad precipitation between GDAS_T254 and observations along (a) 70°–90°, (b) 90°–110°, and (c) 110°–130°E.
Thus, it seems that ICs do not have a strong influence on the model outlooks, which is true at least in these four IC experiments. The differences among the predictions derived from different ICs are much smaller than the differences among the experiments with various model resolutions. The differences produced by different ICs seem to be stochastic errors, and the ensemble means tend to reduce this kind of error.

5. Comparison between initial conditions of GDAS and CDAS

Here, we compare the predictions of monsoons in experiments using the GDAS ICs and CDAS ICs. As in the previous sections for GDAS experiments, we analyze the ensemble means of four CDAS ICs (23 and 28 May, and 3 and 8 June) for three resolutions, namely, CDAS_T62, CDAS_T126, and CDAS_T254, respectively.

Figure 15 shows the different patterns of precipitation between the observations and the predictions from the CDAS experiments (Figs. 15a–c) and the differences between the GDAS and CDAS experiments (Figs. 15d–f). Overall, the error patterns of precipitation in the CDAS experiments and the change in the results with different model resolutions are similar to those in the GDAS experiments discussed in the previous sections. That is, there are wet biases over the Indian Ocean, the southern slope of the Tibetan Plateau, and the Maritime Continent. There are also dry biases over the Indian subcontinent, East Asia, the SCS, and the western Pacific. Increased model resolution partially resolves the problem related to terrain effect on the locations of rainfall centers. However, it also boosts errors over the SCS, the western Pacific, and the Maritime Continent. Compared with the GDAS experiments, the CDAS experiments produce larger errors over most monsoon regions, indicated by the same-sign values in the CDAS–GDAS difference and the GDAS–observations difference. Only over the southern slope of the Tibetan Plateau, the BOB, the SCS, the western Pacific, and the Maritime Continent are the predictions of CDAS better than the predictions of GDAS.

Similar to precipitation predictions, deficiencies in the CDAS ICs when predicting monsoon circulation have almost the same patterns as those of the GDAS experiments (Fig. 16). They produce anomalous westerly flow over the tropical southern Indian Ocean, anomalous anticyclonic circulation over the Indian subcontinent and BOB, and anomalous cyclonic circulation over the western Pacific. All those features indicate weaker-than-observed monsoon circulation in the CDAS experiments. Only at the resolution of T254 (Fig. 16f) does the CDAS experiments simulate stronger monsoon circulation than the GDAS experiments, corresponding to an improvement in precipitation prediction over the BOB, the SCS, the western Pacific, and the Maritime Continent. Given that the increase in model resolution fails to improve the predictions of precipitation and circulation for these regions, the CDAS ICs seem helpful for reducing the negative impacts of higher model resolution on monsoon simulations in experiments with the GDAS ICs for these particular regions.

Figure 17 presents the average precipitation over the above-analyzed three subregions of the Asian summer monsoon (the IP, ICP, and SCS) in the CDAS experiments. Neither the evolution nor the RMSE of the precipitation shows any notable improvement in precipitation prediction when model resolution is increased in the CDAS experiments (also see Table 1). Most CDAS experiments have larger errors than do the GDAS experiments, with the exception of CDAS_T254.

6. Summary

Prediction of the Asian summer monsoon has long been a challenging task of weather and climate prediction.
operations. Nevertheless, numerical models have shown encouraging potential for improving the skill of monsoon predictions on various time scales. Among others, enhanced model resolution and initial conditions have been considered important for improving monsoon prediction skill.

In this study, we have conducted a series of 60-day hindcasts with the NCEP Climate Forecast System to understand the impacts of atmospheric model resolutions and initial conditions on predictions of the Asian summer monsoon. Each of the experiment is integrated for a time period ranging from 2002 to 2006 and has 14 ensemble members. Experiments are conducted at resolutions of T62, T126, and T254, and they are initialized every 5 days from May to August using an operational global atmospheric data assimilation system and operational global ocean data assimilation.

It is found that, in predicting the magnitude and the timing of monsoon rainfall over land areas, high model resolution performs better than lower model resolution. The increase in prediction skills with model resolution is more apparent over South Asia than over Southeast Asia. The largest improvement in rainfall prediction is seen over the Tibetan Plateau. However, the increase in model resolution does not enhance the skill of rainfall predictions over oceans. Over the South China Sea and the Philippine Sea, simulations of monsoon rainfall even become worse from T62 to T254. Accordingly, increases

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**Fig. 15.** Differences in climatological (2002-06) precipitation between CDAS experiments and observation for (a) CDAS_T62 minus observations, (b) CDAS_T126 minus observations, and (c) CDAS_T254 minus observations. (d)-(f) Differences in precipitation between CDAS experiments and GDAS experiments (shaded) and between GDAS experiments and observations (contours).
in model resolutions improve the prediction of the monsoon circulation over land but not ocean. Reasons for the lack of improvement in monsoon simulations and predictions with (atmospheric) model resolution over oceans are unclear at present.

It is also found that model resolution has a larger impact than do the initial conditions on predicting the development of the Asian summer monsoon in the early season. This result is consistent with the features related to predictions of the Asian summer monsoon found when analyzing the monthly and seasonal means of CFS hindcasts with different lead times and long integrations of free runs with the model (Yang et al. 2008b).

It should be pointed out that in this study we have only investigated the different impacts of three model resolutions on monsoon simulations and predictions. It is possible that for some particular regions resolution T254 may still not be high enough to capture the local monsoon features. Previous studies (e.g., Yang et al. 2009) have shown that increasing the model resolution from T62 to T162 can improve CFS simulations of U.S. precipitation over some regions but fails for other regions such as the southwest U.S. monsoon region. Nevertheless, the CFS with resolution T382 may have a much higher level of skill (Weaver et al. 2011) and perhaps this higher resolution is needed to better simulate and predict the Asian summer monsoon. We might also apply other methods to extend the model skill of monsoon (or precipitation) prediction. Detecting the “analog years” between model predictions and observed spatial patterns (Wang and Fan 2009) and forecasting the year-to-year increment of a variable (Fan et al. 2008) have been demonstrated to be effective for enhancing monsoon prediction skill.

Fig. 16. As in Fig. 15, but for 850-hPa winds.
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FIG. 17. Time series of climatological (2002–06) pentad precipitation averaged over the (a) IP, (b) ICP, and (c) SCS for both observations and CDAS experiments.
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